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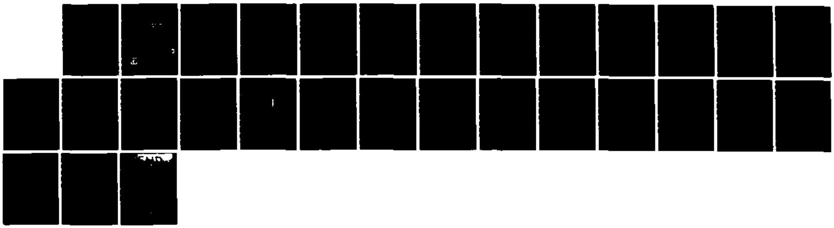

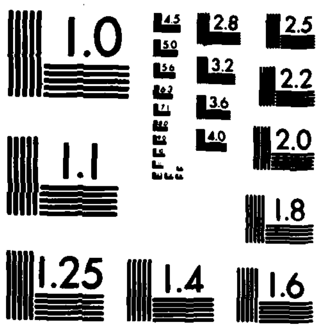

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ACOUSTIC SURFACE WAVE MEASUREMENTS ON LIVE BOTTLENOSE DOLPHINS

BY W. M. MADIGOSKY, G. F. LEE (NSWC),
J. HAUN, F. BORKAT, R. KATAOKA (NOSC)

RESEARCH AND TECHNOLOGY DEPARTMENT

1 SEPTEMBER 1983

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The surface wave velocity and absorption constant were determined on live bottlenose dolphins as a function of position, propagation direction, and frequency. A progressive wave was propagated on the outer skin of a dolphin by an electromagnetic shaker driven by a noise source. Two miniature accelerometers were attached to the skin at a distance of 3.2 cm apart. The output signals from the accelerometers were analyzed by a dual channel Fast Fourier Transform Spectrum Analyzer. The data acquisition was

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further automated by a minicomputer. The surface wave velocities were the highest below the dorsal fin area and the lowest at an area around the posterior insertion of the pectoral fin. Generally, the velocity and absorption constant were independent of the propagation direction (anterior, posterior, dorsal, and ventral) except near the dorsal fin. Over most of the regions measured, the surface wave velocity ranged from 4 to 14 m/sec over the frequency range of 100 to 1000 Hz. The attenuation α (dB/m) was assumed to be $\alpha = Af$ where A is the absorption constant and f is the frequency. The absorption constant was the highest around a line at the posterior insertion of the pectoral fin, 1.5 dB sec/m, and the lowest just below the dorsal fin, 0.5 dB sec/m.

FOREWORD

This report describes the work done on live bottlenose dolphins. The goal of this work was to determine the surface wave velocity and absorption constant as a function of position, propagation direction, and frequency on the skin of a living dolphin. A progressive wave was propagated on the outer skin of a dolphin by an electromagnetic shaker driven by a noise source. Two miniature accelerometers were attached on the skin to measure the response of excited skin.

This work was carried out during FY83 with funds provided by NOSC under 61000N task 511PL22 and the Office of Naval Research under 61153N, NR 657-682.

Approved by:

J. R. DIXON, Head
Materials Division

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INTRODUCTION/BACKGROUND

In 1936, Gray[1] observed that the bottlenose dolphin, Tursiops truncatus, could swim at speeds of 19.7 knots for a period of 7 seconds. If one assumes that the power output of cetaceans equals that of other mammals (0.021 hp/lb body wt), then to reach these speeds under turbulent flow conditions, dolphins must expend several times more power than their muscles can generate. In fact, Lang[2], in 1963 concluded that based on energy considerations, dolphins could not exceed 11 knots for periods greater than 2 hours. This unaccountable difference between energy output and speed is known as Gray's Paradox.

There is no doubt that dolphins are capable of high energy output[3]. Dolphins have the ability to dive deeply (300 to 600 m) for long periods. They have powerful hearts, large circulatory systems, variable heart rates (high when breathing) and large brains. Unfortunately, all this information is insufficient to make a quantitative evaluation of Gray's Paradox from the standpoint of energy expenditures.

Numerous factors could be involved in reducing energy requirements. These include the shape of the body, the elastic and viscoelastic properties of the skin, the elasticity and shape of the impeller, the body and blood temperatures, the blood pressure in the system, the mucous sheath, the production and shedding of tears, the tension in the skin, and finally, a possible dynamic interactive response of the animal's skin. Many authors[4,5] suggest that it is the mechanical properties of dolphin skin which account for the energy output of Gray's Paradox by providing laminar flow at high speeds or by stopping turbulent flow.

There is no doubt that the skin of a dolphin is unique. The dermal papillae contain blood vessels and nerve endings. Dolphins have a circulatory system which can supply pressures up to 7 atmospheres to the dermal papillae.[6] This could possibly change the skin elasticity. Also, it is reported[6] that the dermal papillae are inclined at two different angles (10-25 deg. and 25-40 deg.) at different locations.

The goal of this investigation was to measure dolphin skin properties by determining the acoustic surface wave response of the skin of live dolphins. The dolphins used were Tursiops truncatus or bottlenose dolphins. The approach was to directly measure the surface disturbance properties by measuring the sound speed and attenuation of propagating surface waves on the skin of live dolphins as a function of stimulus frequency and location on the animal. It is hoped that with this data, our knowledge of surface wave propagation in multilayered materials, and the relationship between these waves and the basic elastic moduli of the layers, it will be possible to construct an artificial analog of the dolphin skin and perform controlled drag tests on this analog in a water tunnel.

The work was done at the Naval Ocean Systems Center, San Diego, California in conjunction with the Research Division and the Bioengineering Branch under the sponsorship of the Dolphin Hydrodynamics and Compliant Coating Drag Reduction Programs.

EXPERIMENTAL METHODS AND MATERIALS

The experimental procedure is similiar to that recently developed to characterize the dynamic viscoelastic moduli of materials.[7] In the present experiment a disturbance was initiated on the skin surface by means of a hand-held electromagnetic shaker (Bruel & Kjaer type 4810) and the resulting surface wave propagated along the skin of the dolphin. The surface wave was then sensed by two small, light weight accelerometers (0.5 gram) located a known distance apart and at a small distance away from the wave front initiation point. Since the accelerometers were placed on a line normal to the wavefront, they properly sensed the amplitude and phase of the propagating surface wave at two points a known distance apart. Thus, the wave speed and attenuation could be calculated.

At first, one of the accelerometers (Vibra-Metrics model 9001) was attached directly to the excitation device and the second to the edge of a small suction cup. After the initial tests, it was found that the accelerometers could both be glued directly to the dolphin's skin. The bond strength was sufficient to hold the accelerometers in place, yet they could be easily removed later with no damage to the skin's surface. This method was judged to be far superior and all of the measurements reported here were obtained with this method. Figure 1 shows the test arrangement.

The output signals from the accelerometers were analyzed by a dual channel Fast Fourier Transform spectrum analyzer (Hewlett Packard Spectrum Analyzer 3582A). The analyzer performed the following: digitized and displayed the measured signals as the amplitude of the acceleration ratio, Q (dB), and the phase difference, ϕ (deg), of the two accelerometers, and provided a noise source to drive the shaker. The amplitude and phase of the acceleration ratio were continuously measured over a frequency range of 0 to 1000 Hz. The data were also sampled eight to sixteen times and rms averaged. The acquisition of the data was further automated with a minicomputer (Hewlett Packard 9845 calculator). Figure 2 shows the data acquisition system.

The propagational velocity c_p (m/sec) is given by

$$c_p = 360\ df/\phi \qquad (1)$$

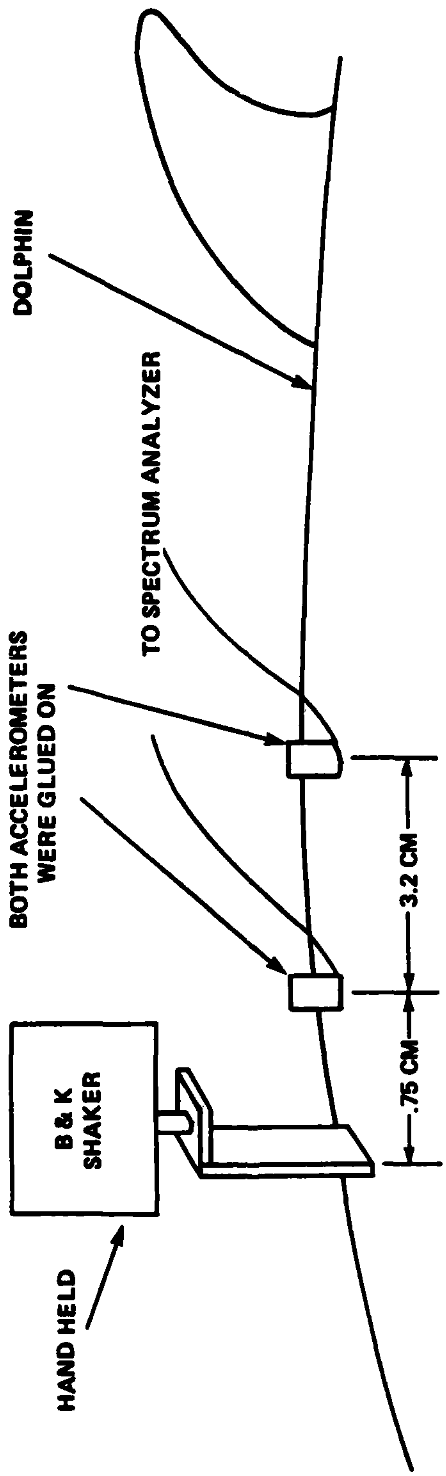

FIGURE 1. DIAGRAM OF THE TEST CONDITIONS SHOWING THE DEVICE FOR INITIATING AND SENSING SURFACE WAVES (3-8 JUN 1983)

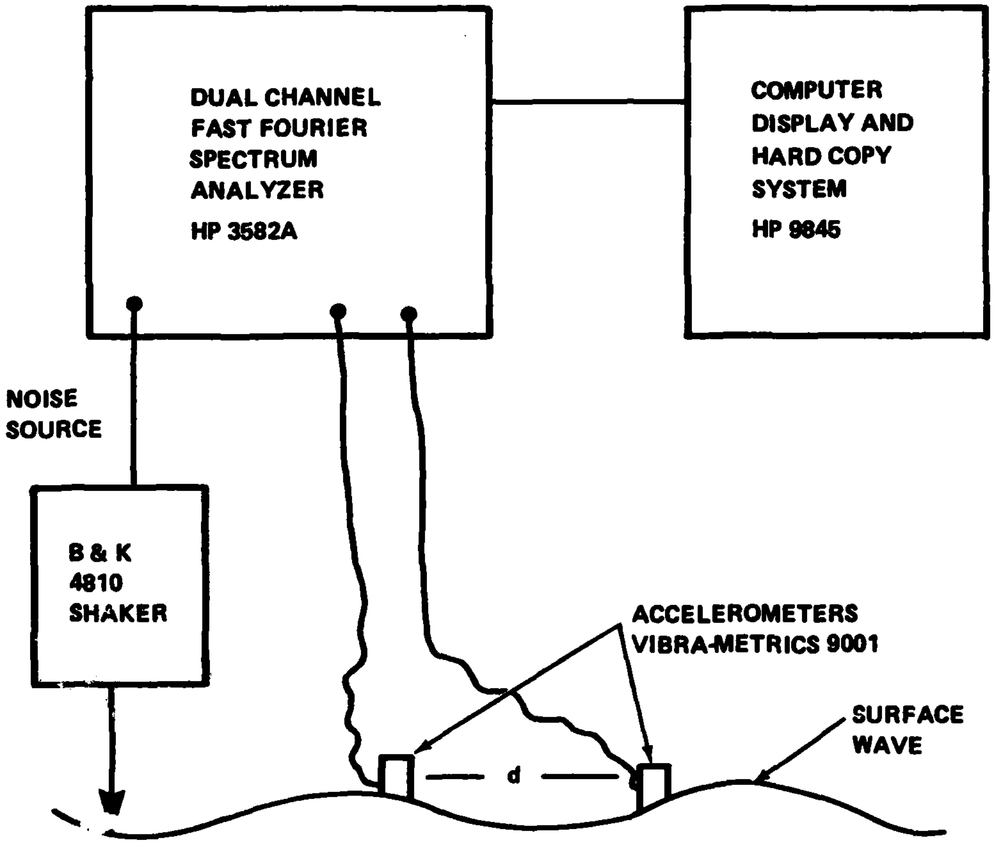

FIGURE 2. BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS FOR OBTAINING SURFACE WAVE SPEEDS AND ATTENUATIONS

where f is the frequency in Hz and d is the distance between the centers of the two accelerometers. It was found that a distance of 3.2 cm between accelerometers gave good results. The attenuation α (dB/m) is given by

$$\alpha = Q/d \tag{2}$$

In most materials the absorption coefficient varies with frequency. For liquids it varies as the square of the frequency while in most rubbers it is roughly proportional to the frequency. After obtaining some data it appeared that the attenuation of surface waves on the dolphin skin also closely followed the first power frequency law. Thus, all of the data was processed according to

$$\alpha = Af \tag{3}$$

where A (dB sec/m) is the absorption constant. The absorption constant is then given by

$$A = Q/(df) \tag{4}$$

Most of a dolphin's skin is soft to the touch and measurements were concentrated in these soft areas. Measurements were also made on the dorsal fin area because it was observed to be harder than the other areas. Areas of scars were avoided because it was felt that the data obtained there would not be meaningful. All measurements were made at approximately 21°C.

Care was taken to determine if there were a difference in propagation velocity depending on the direction of propagation, i.e., anterior, posterior, dorsal, or ventral directions. A mechanical wave can be launched in four different directions. A wave initiated at the tail end of the dolphin that travels toward the head, is labeled as an Anterior Wave Motion (AWM). Obviously, a wave traveling in the opposite direction is a Posterior Wave Motion (PWM). A mechanical wave initiated from the belly that propagates toward the dorsal fin is designated as a Dorsal Wave Motion (DWM). Finally, a mechanical wave launched in the opposite direction is a Ventral Wave Motion (VWM). The shaker is usually positioned 0.64 to 2.54 cm, for instance, behind a posterior accelerometer to propagate an AWM or above a dorsal accelerometer to propagate a VWM.

The positions of the measurements are designated by a letter and a number, i.e. A1, B2, and are shown in the pictorial representation of a dolphin in Figure 3 and described in Table 1.

All measurements were conducted on the upper half of the animal and all but a few were located mid-dorsal and forward (anterior). Again, measurements were concentrated over these areas which were soft to the touch and where it was thought that drag reduction, or delay in transition might occur.

Experiments were conducted on four different animals at various times over a period of several months. Initial tests in March were preliminary and were greatly hampered by bad weather. Final tests were run in June and tests on two of the animals were repeated using an improved setup. In all, six complete days of testing were achieved. Both female and male animals were tested. Each of the animals was removed from its pen and brought into a test lab in a tank large

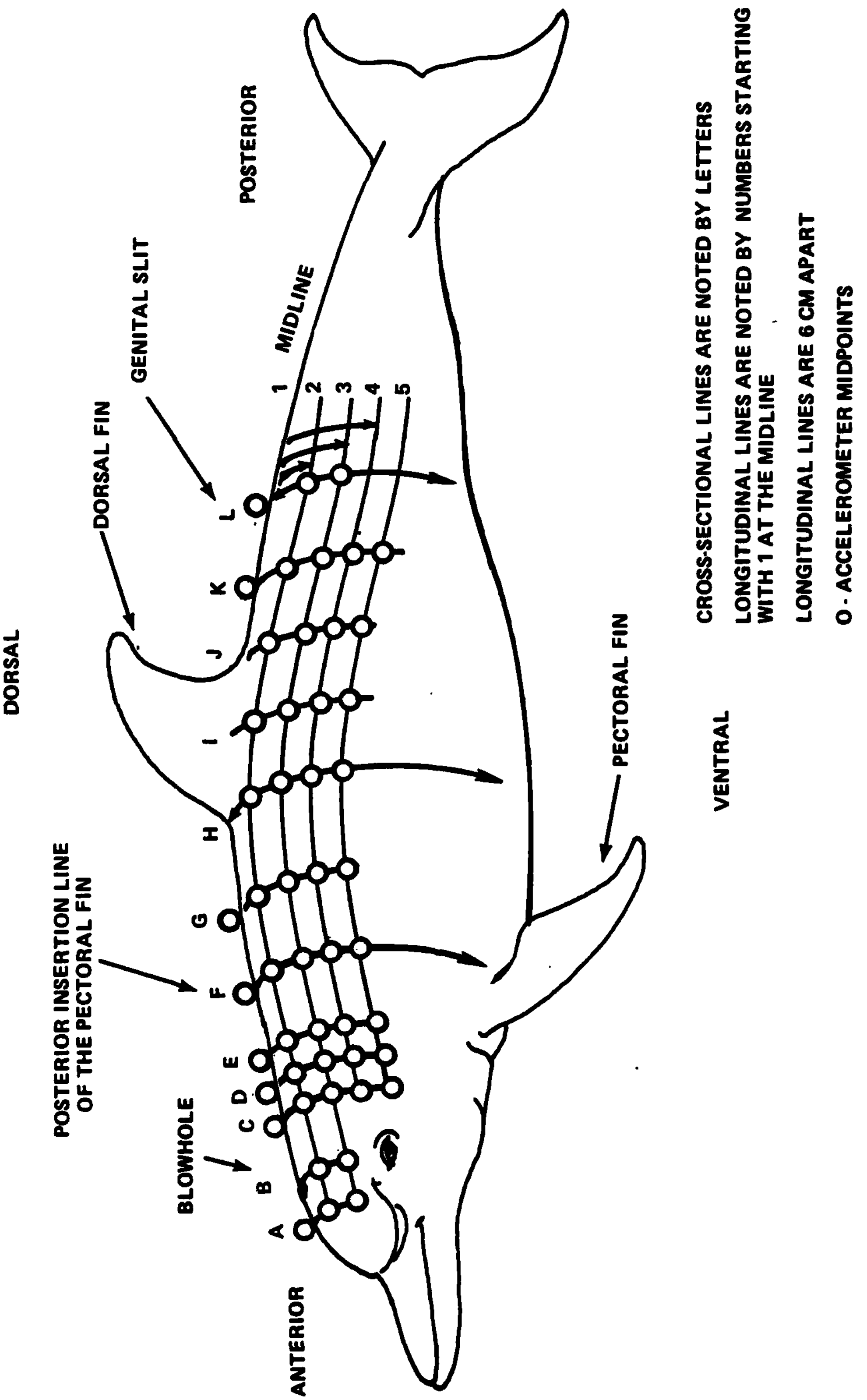

FIGURE 3. DIAGRAM OF BOTTLENOSE DOLPHIN SHOWING THE POSITIONS AND DIRECTIONS FOR WHICH EXPERIMENTAL DATA WERE GATHERED

TABLE 1. ACCELEROMETER MIDPOINT LOCATIONS

Midpoint	Location: Longitudinal Component	Location: Lateral Component
A1	8 cm forward of blowhole on melon	On midline
A2	"	6 cm below midline
A3	"	12 cm " "
B2	On line between blowhole and eye	6 cm below midline
B3	"	12 cm " "
C1	6 cm anterior of "D" cross section	On midline
C2	"	6 cm below midline
C3	"	12 cm " "
C4	"	18 cm " "
D1	Midway between blowhole and posterior insertion of pectoral fin	On midline
D2	Midway between blowhole and posterior insertion of pectoral fin	6 cm below midline
D3	Midway between blowhole and posterior insertion of pectoral fin	12 cm " "
D4	Midway between blowhole and posterior insertion of pectoral fin	18 cm " "
E1	6 cm posterior of "D" cross section	On midline
E2	"	6 cm below midline
E3	"	12 cm " "
E4	"	18 cm " "
E5	"	24 cm " "
F1	At posterior insertion of pectoral fin	On midline
F2	"	6 cm below midline
F3	"	12 cm " "
F4	"	18 cm " "
F5	"	24 cm " "
G1	Midway between posterior insertion of pectoral fin and anterior junction of dorsal fin	On midline
G2	Midway between posterior insertion of pectoral fin and anterior junction of dorsal fin	6 cm below midline

TABLE 1. ACCELEROMETER MIDPOINT LOCATIONS (Cont.)

Midpoint	Location: Longitudinal Component	Location: Lateral Component
G3	Midway between posterior insertion of pectoral fin and anterior junction of dorsal fin	12 cm below midline
G4	Midway between posterior insertion of pectoral fin and anterior junction of dorsal fin	18 cm " "
G5	Midway between posterior insertion of pectoral fin and anterior junction of dorsal fin	24 cm " "
I2	Middle of dorsal fin	6 cm " "
I3	"	12 cm " "
I4	"	18 cm " "

enough for the animal but small enough to constrain its movement. Approximately half the animal was below water. The top of the animal was constantly kept moist.

At the beginning of testing on the fourth animal, Dr. Sam Ridgway was able to acquire a large piece of exterior dolphin skin (epidermal and dermal layers) from an injured dolphin. This outer skin differs from the complete skin which also contains the hypodermis or blubber. The complete skin is approximately 25 mm thick. The epidermal and dermal layers together are 2.7 mm thick. This is the gray skin seen in cross sections (and on the outside) as opposed to the blubber which is white. Having a fresh (approximately 15-minute-old) skin sample to investigate was indeed a bit of serendipity. We quickly measured the dynamic Young's moduli of the sample (Reference 9) in two directions--dorsal-ventral and anterior-posterior. There appeared to be a definite difference in Young's modulus for the two directions. If one assumes a Poisson's ratio close to 1/2 for this material, then shear moduli and velocities can be directly calculated from the moduli. Figure 4 shows the experimental arrangement for measuring Young's modulus.

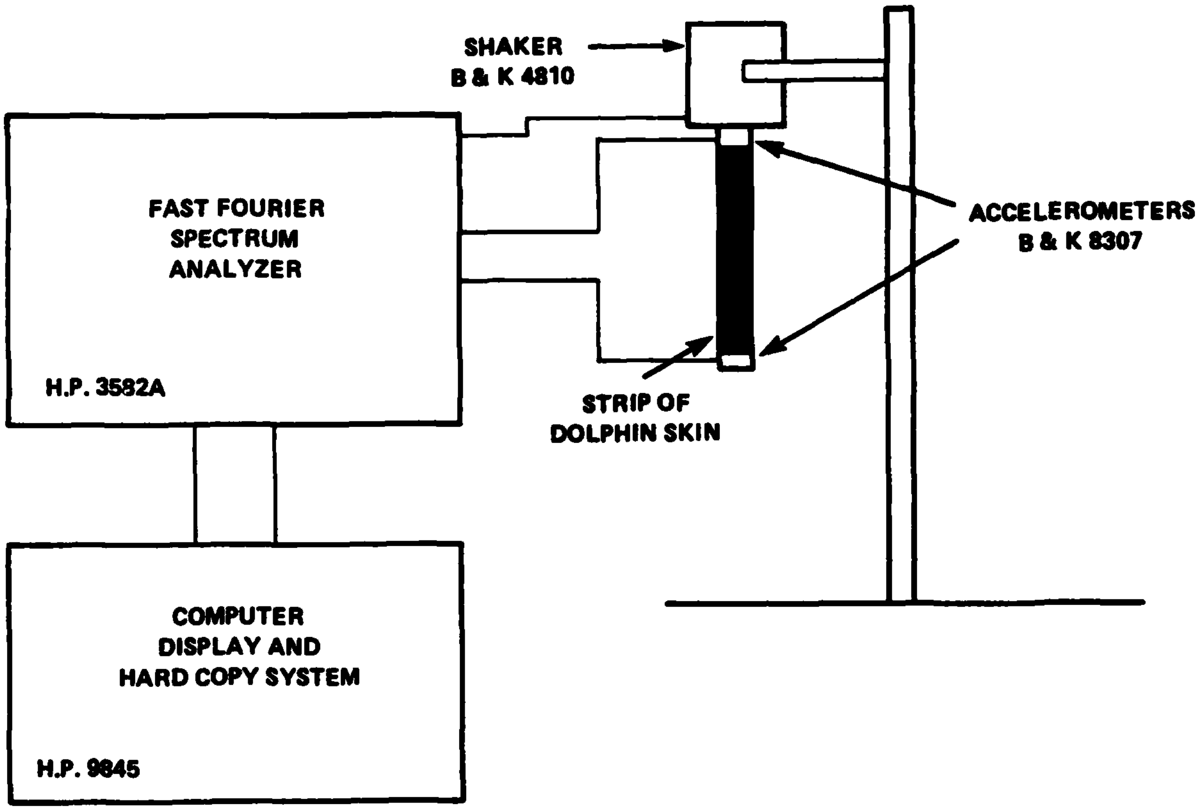

FIGURE 4. TRANSMISSIBILITY APPARATUS FOR MEASURING DYNAMIC YOUNG'S MODULI

RESULTS AND DISCUSSION

The surface wave velocity and absorption constant results are presented in Table 2 for the female dolphin H-17-TT-13F and Table 3 for the male dolphin TT-OM as a function of position, propagation direction, and frequency. The results for both dolphins were similar. The velocities varied with positions where the average velocity at 500 Hz was 7 m/sec over all areas except near the dorsal fin and on the melon. The average velocity increased slightly to 9-13 m/sec for position A1 on the melon. The highest average velocity, approximately 130 m/sec, was found just below the dorsal fin, I2. This area is much harder to the touch. The absorption constant also varied with positions: from 1 to 2 dB sec/m over the majority of the animal, to 0.3 to 0.5 dB sec/m just below the dorsal fin. Generally, the velocity and absorption coefficients were independent of the propagation direction except near the dorsal fin I2-I4. There, the high frequency VWM velocity was lower by a factor of 2 to 5 than the AWM, PWM, and DWM velocities. The absorption constants by contrast were higher by a factor of 2. Over the three frequencies of 100, 500, and 1000 Hz, the velocities increased with increasing frequency. Over most of the animal the velocity increased from 4 to 14 m/s over the 100 to 1000 Hz frequency interval. In contrast, just below the dorsal fin the velocities increased rapidly with frequency rising over 100 m/sec from 100 to 1000 Hz. The absorption constant was assumed to follow the frequency to the first power as mentioned before. Considerable variation was observed in the absorption data. This was no doubt due to experimental difficulties. The attenuation was generally large with the surface wave amplitude decreasing 12-16 dB/cm at 1000 Hz. The average absorption constants are tabulated in Tables 2 and 3. A typical hard copy output from the HP 9845 computer is given in Figure 5.

The results of shear modulus measurements made directly on the exterior skin layers (epidermis and dermis) removed from an injured dolphin are shown in Figure 6. Two samples were cut in two directions, dorsal-ventral (DV) and anterior-posterior (AP). Separate data were obtained on each sample. The shear modulus, G, is plotted as a function of frequency and data are shown for intervals of 15 minutes to 125 hours. Also shown at zero frequency are the results of a static tensile test taken when the sample was approximately one hour old. There is good agreement between the static and dynamic data. Also, there are indications that the sample was degrading with time. The error bars on the static test data indicate our best estimate of the possible error from the slopes of the stress-strain curves.

Table 4 presents the data on the four samples in terms of the shear sound speed ($G = \rho c_s^2$ where ρ was assumed to be 1 gm/cm^3). From the table it is clear that the sound speeds in the DV direction are higher than those in the AP direction. This is somewhat surprising since it is known that the dermal ridges occur in the AP direction and our first inclination would be to expect the skin to be stiffer in that direction. This difference in sound speed, AP vs DV, is not consistent with the fact that we observed no difference in surface wave speeds on the animal. Obviously, the layer underneath (hypodermis or blubber) plays an important role and may be responsible for the isotropic properties of the surface waves on a live animal. We also note from Table 4 that the velocities decrease with increasing time, indicating a degradation in the sample with time.

TABLE 2. VELOCITY AND ABSORPTION CONSTANT AS A FUNCTION OF POSITION, PROPAGATION DIRECTION, AND FREQUENCY FOR THE FEMALE DOLPHIN (H-17-TT-13F)

Position	Propagation Direction	Velocity (m/sec) at 100 Hz	500 Hz	1000 Hz	Absorption Constant (dB sec/m)
A1	AWM	7	9	14	1.0
	PWM	5	6		1.4
A2	AWM	7	8		1.1
	PWM	5	6		1.2
A3	AWM	4	6		1.0
	PWM	6	7		1.5
C2	AWM	6	10	11	1.4
	PWM	6	10	17	1.1
C3	AWM	7	13		1.0
	PWM	6	9		1.0
C4	AWM	4	8		1.2
	PWM	4	8		1.6
E1	AWM	5	6		1.3
	PWM	4	6		1.2
E2	AWM	5	6		1.2
	PWM	5	7		1.3
E3	AWM	5	7		1.5
	PWM	5	7	12	1.0
E4	AWM	4	8		1.1
	PWM	4	6	11	1.2
E5	AWM	4	7		1.4
	PWM	5	7		1.2
F1	AWM	4	6		0.9
	PWM	5	7		1.2
F2	AWM	5	8		0.7
	PWM	4	7		0.9
F3	AWM	5	8		0.8
	PWM	6	7	10	0.7
F4	AWM	4	7		1.3
	PWM	4	7	9	1.1
F5	AWM	5	6		1.3
	PWM	4	6		1.3

TABLE 3. VELOCITY AND ABSORPTION CONSTANT AS A FUNCTION OF POSITION, PROPAGATION DIRECTION, AND FREQUENCY FOR THE MALE DOLPHIN (TT-OM)

Position	Propagation Direction	Velocity (m/sec) at 100 Hz	500 Hz	1000 Hz	Absorption Constant (dB sec/m)
A1	AWM	8	11	15	1.4
	PWM	6	10	15	1.6
	LWM	6	13		1.4
	RWM	5	12	14	1.4
B2	PWM	4	7	10	2.0
B3	PWM	6	8	10	2.1
F1	AWM	4	7		2.0
	PWM	4	6		1.8
F2	AWM	5	7		1.6
	PWM	5	7		1.7
F3	AWM	4	6		2.0
	PWM	4	6		1.9
F4	AWM	4	6		2.2
	PWM	5	6		1.5
G1	PWM	4	8	10	2.3
G2	PWM	4	7	10	2.0
G3	PMW	4	7	10	2.1
G4	PMW	4	7	10	2.1
I2	AWM	12	60	90	0.5
	PWM	15	44	92	0.3
	DWM	13	65	130	0.5
	VWM	10	16	25	1.0
I3	AWM	8	14	24	0.8
	PWM	5	12	23	0.9
	DWM	12	16	23	1.0
	VWM	6	12		0.3
I4	AWM	4	6		2.1
	PWM	5	9		2.0
	DWM	7	16		2.5
	VWM	3	11		2.3

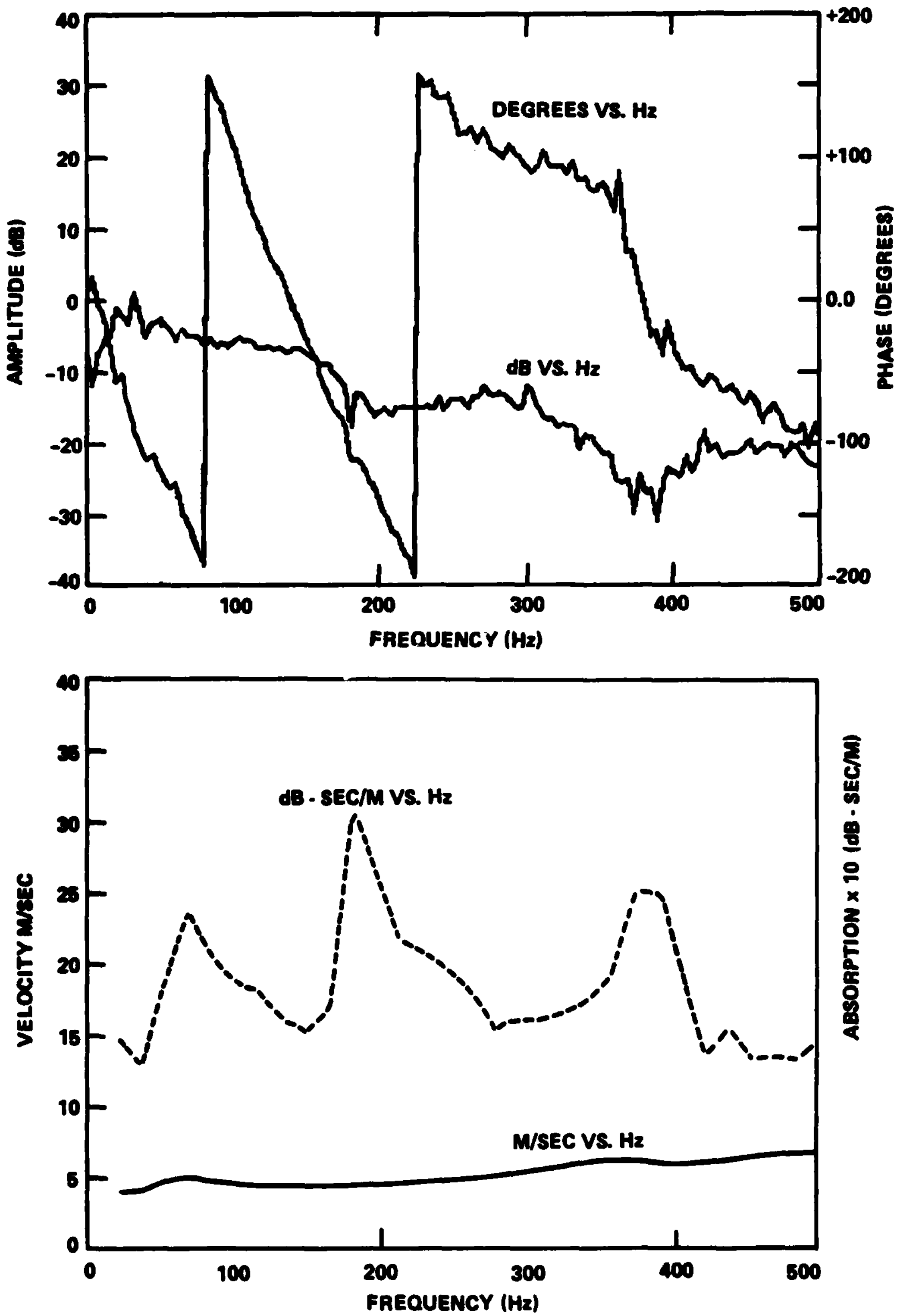

FIGURE 5. TYPICAL HARD COPY OUTPUT FROM THE HP 9845 COMPUTER (UPPER PLOT – AMPLITUDE AND PHASE VERSUS FREQUENCY; LOWER PLOT – ABSORPTION COEFFICIENT A (WHERE α = Af) AND VELOCITY VERSUS FREQUENCY)

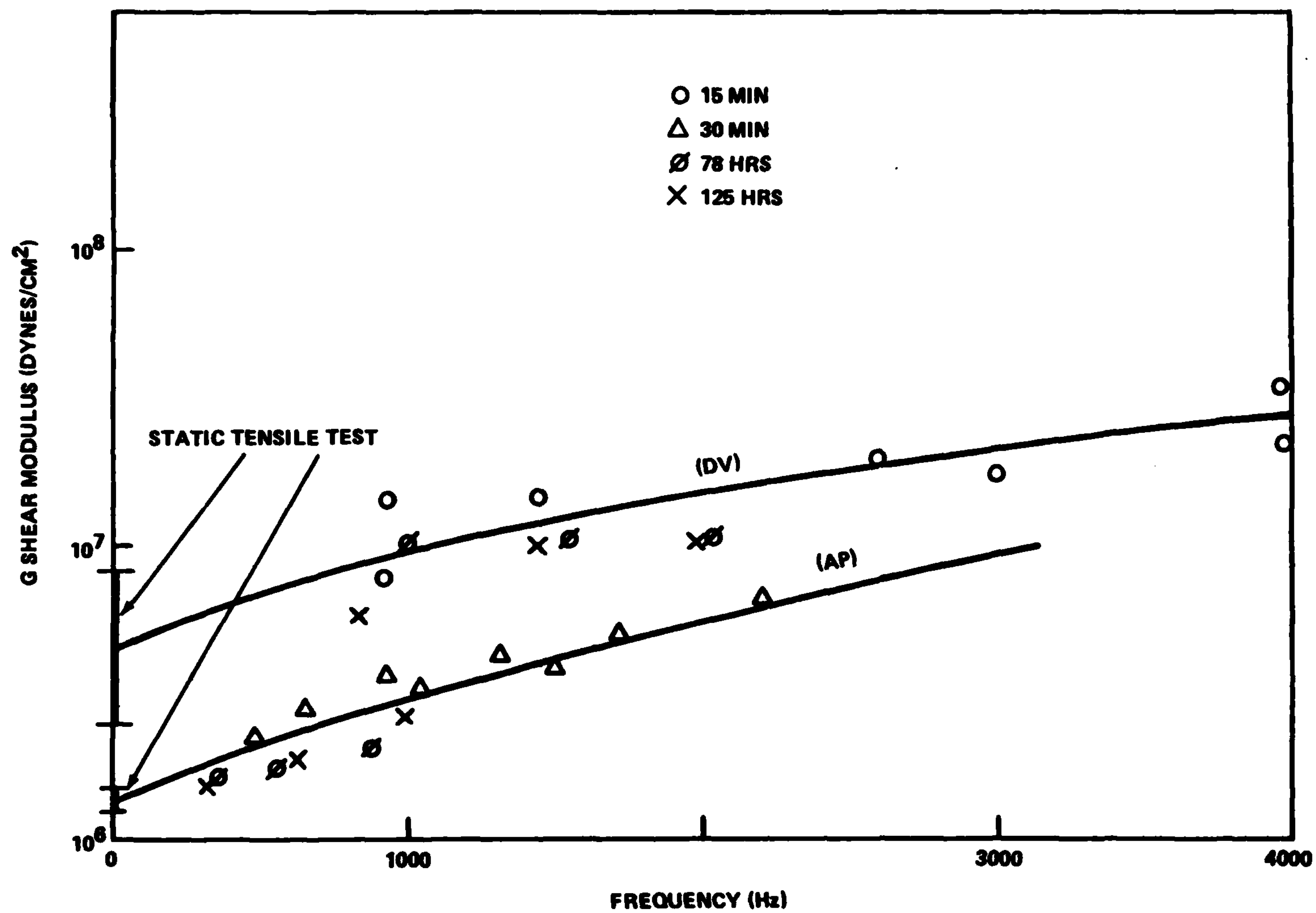

FIGURE 6. SHEAR MODULUS VERSUS FREQUENCY FOR THE OUTER SKIN (EPIDERMIS AND DERMIS) AS A FUNCTION OF TIME AFTER SAMPLE WAS CUT FROM THE ANIMAL. UPPER CURVE FOR SKIN CUT IN DORSAL-VENTRAL DIRECTION; LOWER CURVE FOR SKIN CUT IN ANTERIOR-POSTERIOR DIRECTION. ALSO SHOWN AND PLOTTED AT ZERO FREQUENCY ARE THE STATIC DATA OBTAINED ON A TENSILE TESTING MACHINE.

TABLE 4. MEASURED SHEAR WAVE VELOCITIES (M/SEC) OF EXTERIOR SKIN SAMPLES FOR TWO DIRECTIONS--DORSAL-VENTRAL (DV) AND ANTERIOR-POSTERIOR (AP)--AS A FUNCTION OF FREQUENCY (Hz) AND TIME

After 15 min				After 30 min			
DV1		DV2		AP1		AP2	
f	C_s	f	C_s	f	C_s	f	C_s
920	38.0	920	30.0	480	18.5	650	20.8
1450	40.2	1540	33.2	920	23.1	1050	22.5
2600	54.3	3000	48.5	1320	24.8	1500	24.2
4350	72.2	4400	57.2	1720	26.0	2200	28.3

After 78 hrs				After 125 hrs			
DV2		AP1		DV2		AP1	
f	C_s	f	C_s	f	C_s	f	C_s
1000	32.3	360	14.5	808	26.2	345	13.9
1550	33.5	560	15.2	1440	31.0	616	16.7
2050	33.1	880	17.8	1990	32.4	1000	20.2

NOTE: Designations 1 and 2 refer to two different samples.

CONCLUSIONS

The surface wave velocity and absorption constant were determined on live bottlenose dolphins as a function of position, propagation direction, and frequency. Based on the results, the following conclusions have been reached:

- The velocity and absorption constant were independent of propagation direction, except near the dorsal fin.

- Over most of the regions measured, the surface wave velocity ranged from 4 to 14 m/sec over the frequency interval 100 to 1000 Hz. In contrast, below the dorsal fin the velocity increased rapidly from 10 to 130 m/sec over the same frequency interval.

- The absorption was found to be proportional to the frequency, $\alpha = AF$. Over most of the animal the constant A was found to be 1.5 dB sec/m. In contrast below the dorsal fin A = 0.5 dB sec/m.

- The velocities at 500 Hz are the highest just below the dorsal fin (65 m/sec), and the lowest in an area around the line at the posterior insertion of the pectoral fin (6 m/sec).

- Finally, it appears from the low surface wave speeds observed on the live animal, compared to the much higher shear wave speeds observed on a separated epidermis plus dermis sample, that the entire 25 mm skin (epidermis, dermis and hypodermis) plays a role in determining the compliant coating surface response of the dolphins. We note that the Kramer coating attempted to duplicate only the epidermis plus dermis layers. The data presented here suggest that the hypodermis is an integral part of the skin and plays an important role in determining the compliant coating response to hydrodynamic disturbances.

Future work will address the task of defining the material parameters (elastic moduli) and dimensions that would constitute an artificial analog of the dolphin skin. The remaining task would then be the preparation of materials which meet the above specifications and construction of the actual layer or layers. Concurrently, the Soviet literature and input from theoretical studies on compliant layers need to be evaluated and integrated into the final design.

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